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Preprint typeset using L^AT_EX style emulatej v. 5/2/11DETECTION OF VHE γ -RAYS FROM HESS J0632+057 DURING THE 2011 FEBRUARY X-RAY OUTBURST WITH THE MAGIC TELESCOPES

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ABSTRACT

The very high energy (VHE) γ -ray source HESS J0632+057 has recently been confirmed to be a γ -ray binary. The optical counterpart is the Be star MWC 148, and a compact object of unknown nature orbits it every ~ 321 d with a high eccentricity of ~ 0.8 . We monitored HESS J0632+057 with the stereoscopic MAGIC telescopes from 2010 October to 2011 March and detected significant VHE γ -ray emission during 2011 February, when the system exhibited an X-ray outburst. We find no γ -ray signal in the other observation periods when the system did not show increased X-ray flux. Thus HESS J0632+057 exhibits γ -ray variability on timescales of the order of one to two months possibly linked to the X-ray outburst that takes place about 100 days after the periastron passage. Furthermore our measurements provide for the first time the γ -ray spectrum down to about 140 GeV and indicate no turnover of the spectrum at low energies. We compare the properties of HESS J0632+057 with the similar γ -ray binary LS I +61°303, and discuss on the possible origin of the multi-wavelength emission of the source.

Subject headings: binaries: general — gamma rays: general — stars: individual (MWC 148) — X-rays: binaries — X-rays: individual (HESS J0632+057)

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1. INTRODUCTION

With the advent of the new generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) such as MAGIC, HESS and VERITAS, a new source class, the γ -ray binaries, was established. Only few members of this class are known to date. Among these objects LS I +61°303, LS 5039 and PSR B1259–63 are regularly detected at very high energy (VHE, $E > 100$ GeV) γ -rays. All of these three systems show variable or even periodic VHE γ -ray emission, and are spatially unresolvable by the current generation of IACTs (Aharonian et al. 2005; Albert et al. 2006; Aharonian et al. 2006; Albert et al. 2009).

HESS J0632+057 was discovered as an unidentified point-like VHE γ -ray source but was considered to be a γ -ray binary candidate because of its spatial coincidence with the Be star MWC 148 (Aharonian et al. 2007; Hinton et al. 2009). The system was observed by VERITAS in VHE γ -rays from 2006 to 2009 with sparse sampling and the measurements did not yield any γ -ray signal (Acciari et al. 2009). The derived flux upper limits above 1 TeV were significantly below the previous detections, thus suggesting that HESS J0632+057 was variable in VHE γ -rays. Since all variable galactic VHE γ -ray sources known to date are associated with binary systems³³, HESS J0632+057 was a very good binary candidate. The here in detail presented VHE γ -ray detection simultaneously to the X-ray outburst in 2011 February was very recently announced by MAGIC and VERITAS (Ong 2011; Mariotti 2011; Jogler et al. 2011; Maier et al. 2011).

Measurements in soft X-rays with *XMM-Newton* detected an X-ray source (XMMU J063259.3+054801) at the position of MWC 148 (Hinton et al. 2009). The X-ray emission is well described by a hard power-law spectrum with energy spectral index $\Gamma = 1.26 \pm 0.04$, consistent with emission of synchrotron radiation from VHE electrons, although a multi-temperature spectral model can also reasonably describe the data. Furthermore, the X-ray source showed a variable flux, without changing the spectral shape. A similar behavior is seen, e.g., in the γ -ray binary LS I +61°303 (e.g. Anderhub et al. 2009). Later X-ray observations with *Swift*/XRT found the source but at a different flux level and with a softer spectral index (Falcone et al. 2010). Recently published *Swift*/XRT observations from 2009 to 2011, display outbursts in the X-ray light curve from HESS J0632+057 with a periodicity of $P = 321 \pm 5$ days (Bongiorno et al. 2011). These measurements also provided evidence for hardness ratio changes with orbital phase. The periodic X-ray emission is a strong evidence for HESS J0632+057 being a γ -ray binary. *Chandra* high time resolution X-ray measurements during the 2011 February X-ray outburst have been used to search for pulsed X-ray emission, but none was detected. Thus the nature of the compact companion of MWC 148 remains unknown (Rea & Torres 2011).

The region of HESS J0632+057 has also been observed at radio wavelengths. The measurements conducted in 2008 with the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT) at 5 and 1.28 GHz, respectively, exhibited an unresolved radio source within the position uncertainties of the VHE γ -ray source and the Be star MWC 148 (Skilton et al. 2009). A flux increase in the 5 GHz band from 0.19 ± 0.04 to 0.41 ± 0.04 mJy showed the vari-

ability of the source on timescales of at least one month. The radio data was well described by a power law spectrum with energy spectral index $\alpha = 0.6 \pm 0.2$ using non-simultaneous data from 1.28 GHz and 5 GHz. No extended structures beyond the two arcsecond resolution were detected. During the 2011 February X-ray outburst very high resolution European Very Long Baseline Interferometry Network (EVN) observations revealed a point-like source coincident with the Be star MWC 148 within uncertainties, which evolved into an extended source with a projected size of about 75 AU (assuming a 1.5 kpc distance), 30 days later (Moldón et al. 2011). The peak of the emission was displaced 21 AU between runs, which is bigger than the orbit size (semi-major axis ~ 2.4 AU). The brightness temperature of the source was above 2×10^6 K hinting to a non thermal origin of the particles producing the radio emission. The morphology, size, and displacement on AU scales were similar to those found in the other gamma-ray binaries, supporting a similar nature for HESS J0632+057 (Moldón et al. 2011). Further high resolution measurements will be needed to understand possible morphological changes in the radio structures along with the orbital phase.

Optical radial velocity measurements were taken on MWC 148 to verify if it is a member of a binary system and determine its orbital parameters (Aragona et al. 2010). No significant radial velocities were found at that time and simulations yielded a lower limit on the possible period of the system of $P > 100$ days compatible with the period found later in X-rays. Finally, radial velocity measurements with the Liverpool telescope obtained from 2008 to 2011 have proven the binary nature of HESS J0632+057/MWC 148. Fixing the orbital period to 321 days as obtained from the X-ray measurements by Bongiorno et al. (2011) these measurements provide for the first time the orbital parameters of the binary system. The compact object orbits MWC 148 on a highly eccentric ($e = 0.83 \pm 0.08$) orbit where the periastron passage occurs at phase $\phi_{\text{per}} = 0.967 \pm 0.008$ using $T_0 = \text{MJD}54857.0$ (Casares et al. 2012).

In this paper, we present the VHE γ -ray measurements of HESS J0632+057 by MAGIC from 2010 October to 2011 March. In particular we detect VHE γ -rays only during an X-ray outburst in 2011 February and measure for the first time the spectrum down to 140 GeV.

2. OBSERVATIONS

The observations of HESS J0632+057 were performed using the MAGIC telescopes on the Canary island of La Palma (28.75°N, 17.86°W, 2225 m a.s.l.), from where HESS J0632+057 is observable at zenith angles above 22°. The MAGIC stereo system consists of two imaging air Cherenkov telescopes, each with a 17 m diameter mirror. Each telescope features a pixelized photomultiplier tube camera with a field of view of about 3.5°. The observations were carried out in stereo mode, meaning that only shower images which simultaneously trigger both telescopes are recorded. The stereoscopic observation mode provides a sensitivity so that a 5σ signal above 300 GeV is detected from a source which exhibits 0.8% of the Crab Nebula flux in 50 hours effective time. The angular resolution is better than 0.07° above several hundred GeV and the energy resolution is 16%. Further details on the design and performance of the MAGIC stereo system can be found in Aleksić et al. (2011).

We observed HESS J0632+057 between 2010 October and 2011 March for a total of 10.6 hours. All observations were

³³ The Crab Nebula is variable at GeV energies, but no confirmed TeV variability has been measured up to now and thus it is not counted among the variable VHE γ -ray sources.

carried out under moonlight conditions and at zenith angles from 22 to 50°. The source was observed for several nights in each month and each of these observation sets are separated by about 20 days. This strategy maximizes the possibility to detect emission from HESS J0632+057 in case of a long orbital period and with the system being active only during a short period of its orbit i.e. one observation cycle. Due to bad weather no data were recorded in 2010 November and 2011 January.

3. DATA ANALYSIS

The data analysis was performed with the standard MAGIC analysis and reconstruction software (MARS). Events that triggered both telescopes were recorded and further processed. The recorded shower images were calibrated, cleaned and used to calculate image parameters individually for each telescope. The energy of each event was then estimated using look-up tables generated by Monte Carlo (MC) simulated γ -ray events. In another step, further parameters, e.g. the height of the shower maximum and the impact parameter from each telescope, were calculated. The gamma/hadron classifications and reconstructions of the incoming direction of the primary particles were performed using the Random Forest (RF) method (Albert et al. 2008). The RF calculates the probability for each event to be of hadronic origin and denotes this parameter as the hadronness of the event. The signal selection uses cuts in the hadronness and in the squared angular distance between the shower pointing direction and the source position (θ^2). The energy-dependent cut values were determined by optimizing them on a sample of events recorded from the Crab Nebula under the same zenith angle range and similar epochs to HESS J0632+057 data. For the energy spectrum and flux, the effective detector area was estimated by applying the same cuts used on the data sample to a sample of MC-simulated γ -rays. Finally, the spectrum was unfolded in energy, accounting for the energy resolution and possible energy reconstruction bias (Albert et al. 2007).

The cuts used for producing the θ^2 -plot for the detection were optimized on a Crab Nebula data sample to yield the best sensitivity and have a higher energy threshold compared to the cuts used to produce the spectrum. For the light curve and integral flux calculations we chose a conservative energy threshold of $E_{\text{th}} = 200$ GeV, while the spectrum shows reconstructed signals down to 136 GeV. Note that the systematic uncertainties at the lowest energies dominate the total measurement uncertainties. Using a higher energy threshold, 200 GeV, guarantees smaller systematic uncertainties for the light curve and thus yields a better comparison to measurements from other instruments.

4. RESULTS

We detect VHE γ -ray emission from the HESS J0632+057 data set recorded in 2011 February, at an orbital phase separation of ~ 0.3 after periastron, with a significance of 6.1σ in 5.6 hours (see Figure 1). The VHE γ -ray source is not resolved by MAGIC and its extension must be smaller than the MAGIC point spread function, whose Gaussian sigma is 0.09 deg above 200 GeV. We obtain an integral flux of $F(E > 200 \text{ GeV}) = (8.8 \pm 1.7_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ which corresponds to about 4% of the Crab Nebula flux. Previously reported detections (Aharonian et al. 2007) measured the flux only above 1 TeV but agree well within the statistical uncertainties of our measurements when their spectrum is extended to our lower energy threshold. Thus we conclude that dur-

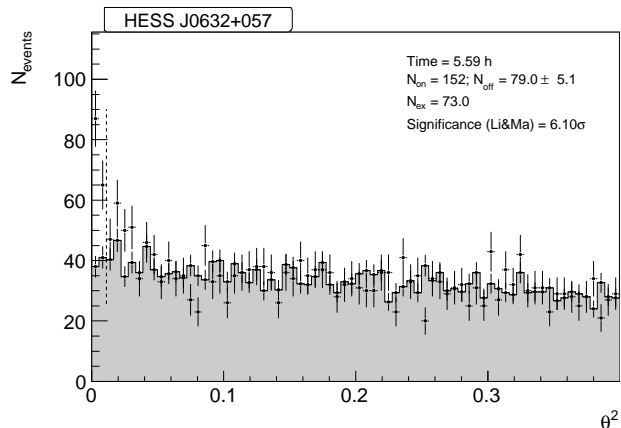


FIG. 1.— The squared angular distance between pointing direction of the shower and the source position (θ^2 -plot) for the position of HESS J0632+057 (points) and the simultaneous determined background regions (grey shaded histogram) for the entire 2011 February MAGIC data set. The significance is calculated according to Li & Ma (1983). N_{on} is the number of events at the source position, N_{off} is the number of background events, N_{ex} is the number of excess events ($N_{\text{ex}} = N_{\text{on}} - N_{\text{off}}$).

ing our observations, HESS J0632+057 exhibited similarly intense VHE emission to the previously detected active VHE γ -ray episodes (Aharonian et al. 2007).

The system was only detected in the 2011 February data during the X-ray outburst observed by *Swift*. No indication of significant emission was found in the data from 2010 October, 2010 December or 2011 March. We denote these three months as the *non-detection period* (NDP). The integration time in the individual months of the NDP is, however, relatively short compared to the 2011 February and we combine the NDP to have the highest possible sensitivity for a baseline VHE flux. We obtain a flux upper limit for the NDP of $F(E > 200 \text{ GeV}) < 3.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at the 95% confidence level following the method suggested by Rolke et al. (2005). Our flux upper limit excludes a baseline emission down to the level of 1.7% of the Crab Nebula flux. No individual night during the quiescent γ -ray state shows any indication of a signal.

We show in Figure 2 the obtained light curve above 200 GeV of HESS J0632+057 for the nightly averages. The VHE gamma-ray source exhibits variability timescales of about one month. Faster variability is possible but to detect it a denser sampling of the LC is needed. However, no short timescale (days) variability is observed during the period of γ -ray activity in 2011 February. Under the assumption that there is no short-time variability in the time period when no VHE γ -ray emission is detected we conclude that the system shows flux variations of at least a factor of two between its quiescent and active state and that the active state must last between 20 and 80 days in the VHE regime.

A correlation of the VHE γ -ray emission with the 2011 February X-ray outburst is suggestive but can not be proven statistically with our sparsely sampled light curve. More extensive observations in VHEs are needed for individual night correlation studies. Note that only in the time of high X-ray activity the system was detected by MAGIC. Whereas the X-ray light curve shows a clear peak shape for the outburst, the VHE light curve during the γ -ray activity shows a constant flux and no variability. Whether this constant γ -ray flux is an artifact of the sparse sampling or a real characteristic of the outburst cannot be determined with these limited data. Note that a similar peak profile as in the X-ray outburst could be

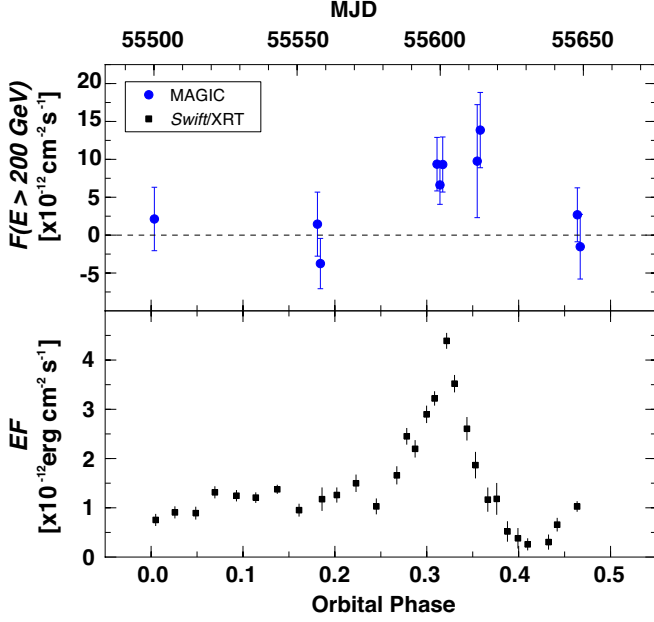


FIG. 2.— The light curve of HESS J0632+057 above 200 GeV is shown in blue for the MAGIC observations (upper panel) and the *Swift*/XRT data between 2 and 10 keV (lower panel) during the same orbital cycle as the MAGIC data in black. Significant emission in VHE is found only in 2011 February for the duration of about one month contemporary to the X-ray outburst. No variability in VHEs is seen during the active state. All error bars show the one-sigma statistical uncertainties.

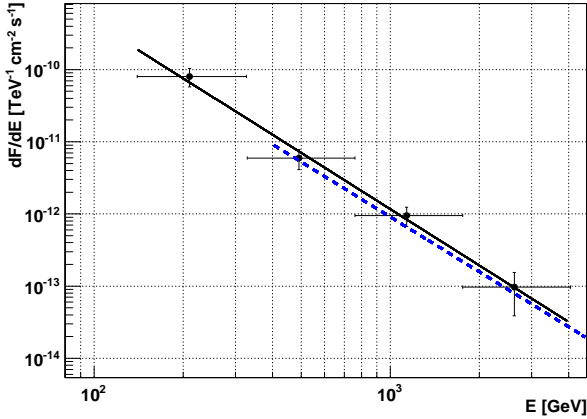


FIG. 3.— Differential energy spectrum of HESS J0632+057 between 136 GeV and 4 TeV. The horizontal error bars represent the bin width whereas the vertical ones show the one-sigma statistical uncertainty. The spectrum is well described by the fitted simple power law with $\Gamma = -2.6 \pm 0.3_{\text{stat}} \pm 0.2_{\text{syst}}$ shown as the black line. The dashed (blue) line is the spectrum obtained by H.E.S.S. between 2004 March and 2006 March, and is in good agreement with our measurement.

present in the VHE light curve.

We obtained a spectrum from the 2011 February data set and it is compatible with a simple power law (see Figure 3) with photon spectral index $2.6 \pm 0.3_{\text{stat}} \pm 0.2_{\text{syst}}$ and normalization $(1.2 \pm 0.3_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. The measured photon index is in very good agreement with the one previously published by H.E.S.S. ($\Gamma = 2.53 \pm 0.26_{\text{stat}} \pm 0.2_{\text{syst}}$), although their spectrum was obtained at energies above 400 GeV (Aharonian et al. 2007). No indication of a turnover is found in the newly opened energy range by MAGIC.

5. DISCUSSION

The VHE gamma-ray data obtained during the periodic X-ray outburst of HESS J0632+057 that took place during 2011 February suggests that the VHE light curve shows similar outbursts like the X-ray light curve. The detection of VHE γ -ray emission only during the X-ray outburst suggests a common origin although our data are too sparsely sampled to allow night to night correlation studies. The MAGIC detection of the source during the peak of the X-ray outburst yielded a similar flux level and energy spectrum as those obtained by HESS four years before (Aharonian et al. 2007). Similar spectral shape and flux levels indicate that the same processes might be at work during the γ -ray active states. In case of a periodic modulation with a period of about 321 days, such a behavior would be expected.

For the first time we could measure the spectrum of HESS J0632+057 between 136 and 400 GeV, and find no evidence for a spectral break or a deviation from a simple power law. This is a common feature found in other binaries which exhibit outbursts (e.g. LS I +61°303 Albert et al. 2009). Thus the turnover in the spectrum must lie below the energy threshold of our observations. All currently known γ -ray binaries show their maximum emission in the high MeV to GeV energy range. This might be the case for HESS J0632+057 although it has not yet been detected by *Fermi*/LAT. The integration time required to detect HESS J0632+057 with *Fermi*/LAT will depend strongly on the source's duty cycle and the spectral properties at MeV to GeV energies.

In several recent publications the similarity between HESS J0632+057 and LS I +61°303 was stressed based on their similar multiwavelength emission (e.g. Hinton et al. 2009, Skilton et al. 2009). We note that there might be some differences in the VHE emission. LS I +61°303 shows complex VHE behavior such as variability on timescales as short as one day (e.g. Anderhub et al. 2009), and different VHE γ -ray flux states (Acciari et al. 2011; Aleksić et al. 2012). Revealing similar behavior in HESS J0632+057, requires higher sensitivity and better temporal sampled data than available to date and thus the degree of similarity between LS I +61°303 and HESS J0632+057 might be smaller compared to the contemporary view. Interestingly, the orbital phase lag for the detected VHE γ -ray emission in HESS J0632+057 is quite close to that in LS I +61°303, about 0.3 after periastron passage (Li et al. 2011; Casares et al. 2012). Similar processes might produce both the X-ray and the VHE γ -ray radiation. However, different spatial- and time-scales of the emitter, given the wider and more eccentric orbit in HESS J0632+057, and different star-emitter-observer geometries (important in the leptonic scenario), make any direct comparison difficult. A proper characterization of the radiation and magnetic fields, and of possible adiabatic losses, is required. Said that, however, we can interpret our HESS J0632+057 data in the context of the X-ray data, as done for LS I +61°303 (see Anderhub et al. 2009).

In the case of LS I +61°303, the X-ray/VHE emission was suggested to originate from a homogeneous leptonic emitter relatively close to the compact object under dominant IC losses. This scenario, already explored in Hinton et al. (2009), is supported by the similar fluxes in X-rays and VHE, which is hard to explain in the context of an homogeneous emitter producing γ -rays (and the X-ray emitting e^{\pm} -pairs) via proton-proton collisions. In the case of HESS J0632+057, however, the X-ray luminosity is slightly lower than the VHE

luminosity. Although in this case the fluxes and spectra still allow the leptonic homogeneous scenario with dominant IC losses, a hadronic homogeneous emitter cannot be discarded. Therefore the question of the hadronic or leptonic nature of the emitter in HESS J0632+057 remains unsolved.

To distinguish between the hadronic and leptonic pictures, and the one population hypothesis for the VHE γ -ray and the X-ray emission needs a better sampling of the light curve at the relevant orbital phases. A spectral index correlation study would shed light on the origin of the emission. Such a study will require long and frequent individual night observations to provide high enough sensitivity for more precise spectral information. Fortunately, due to the X-ray periodicity, such measurements can be planned well in advance. Complementary information from the GeV band will also be valuable, e.g. revealing the spectral shape in the currently unmeasured energy range below 100 GeV and above 100 MeV since this information could reveal the population(s), of particles involved

in the emission processes.

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Facilities: MAGIC

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